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OPTICAL TEST OF THE SPACE SHUTTLE OVERHEAD WINDOWS (U)

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MAY 1990

Final Report for August 1989 - April 1990.

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NOTICES

TECHNICAL REVIEW AND APPROVAL

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Regulation 169-3.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

CHARLES BATES, JR.
Director, Human Engineering Division
Armstrong Aerospace Medical Research Laboratory

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An optical test of the space shuttle overhead windows was performed to determine how the overhead windows would affect the resolution of in-cabin telescopes such as the Spaceborne Direct-View Optical System (SpaDVOS). The test consisted of four subjects viewing a resolution target through the windows with a telescope composed of the SpaDVOS objective lens and an eyepiece. Data were recorded for three focal lengths, five aperture settings, and nine window conditions. The results showed the effect of the windows on resolution was not significant at apertures less than approximately two inches. However, the windows did degrade performance for the larger aperture settings. A photographic test and an independent visual test performed by the Aerospace Corporation corroborated these results.

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Summary

This report documents an optical test of the space shuttle overhead windows performed at the Corning Glassworks plant in Canton, New York, on 1-3 August 1989. The purpose of the test was to determine how the overhead windows would affect the resolution of an in-cabin optical telescope such as the Spaceborne Direct-View Optical System (SpaDVOS).

The test consisted of four subjects viewing a 1951 Air Force tri-bar resolution target through the windows using a telescope composed of the SpaDVOS objective lens and an eyepiece. Data were recorded for three focal lengths, five aperture settings, and nine window conditions. Photographs of the resolution target were also taken at each condition.

The results showed that at apertures less than approximately two inches the effect of the windows on resolution was not significant. However, at larger apertures the windows degraded performance as expected. The photographic test corroborated this result, as did an independent test performed on the same days by the Aerospace Corporation.

The maximum resolution achieved through the window assembly for the subject group was 5.76 line pairs per millimeter at the target plane. This corresponds to a ground resolution of 9.0 ft for the SpaDVOS at maximum magnification flying on a typical shuttle mission with an orbital altitude of 160 nautical miles. Without window degradation, a resolution of 8.0 ft would be expected.

Preface

This report was prepared under work unit 6893-11-02 by members of Crew Systems Effectiveness Branch, Human Engineering Division, Armstrong Aerospace Medical Research Laboratory (AAMRL/HEF), Wright-Patterson Air Force Base, Ohio. Funding was provided by the Human Systems Division's Space Crew Enhancement Advanced Development program, Human Systems Division (HSD/YAS), Brooks Air Force Base, Texas. The authors thank Major Michael Block (AAMRL/HEF) for his part in collecting the data upon which this report is based.

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Introduction

This report documents an optical test of a set of space shuttle overhead windows performed at the Corning Glassworks plant in Canton, New York, on 1-3 August 1989. The purpose of the test was to determine the effect of the overhead windows on the quality of images observed through the windows using long focal length, moderate to large aperture optical systems. These tests were performed by Major Michael G. Block of the Aerospace Medical Research Laboratory (AAMRL/HEF) with the assistance of Captain Robert S. Hoskins of the Human Systems Division (HSD/YAS). Other optical tests were performed by personnel from the Aerospace Corporation, and will be published separately by that organization.

1.1 Background

Observations and photography of the Earth are conducted routinely on every space shuttle mission. Because of their location and relatively large viewing area, the overhead windows of the aft flight deck of the shuttle are the preferred location for conducting these activities (see figure 1.1). Additionally, the shuttle usually orbits in an attitude with these windows facing earthward.

Though the windows have successfully supported observations and photography using low magnification optical systems with relatively small apertures, it is not known how well the windows will support observations through optical systems with larger apertures and higher magnifications. Anecdotal information from the NASA Johnson Space Center Earth Observation Group suggests that the best quality photographs are obtained with apertures of about one inch. However, no data exist to substantiate this report.

The optical tests described in this report were performed in direct support of the Spaceborne Direct-View Optical System (SpaDVOS) Experiment. The SpaDVOS is a folded optical path telescope system designed to mount inside the cabin of the shuttle for viewing out of the overhead windows. It will be used to investigate man's real-time capability to

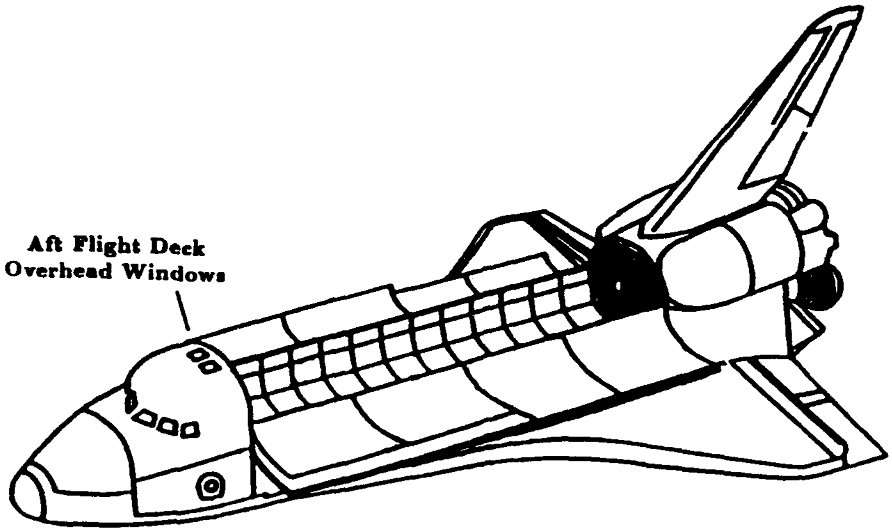

Figure 1.1: Illustration of the space shuttle showing the location of the overhead windows.

view and extract information from sites on the Earth. This investigation involves analysis of the various factors which influence visual performance through the overhead windows, including the windows themselves. As a principal element in the optical path, knowledge of the characteristics of the overhead windows is critical to an objective assessment of the astronaut's performance abilities during the experiment.

1.2 Theory

Two basic phenomena limit the resolution of an optical system. The first is the wave front distortion caused by the various media in the optical path. This distortion is the result of physical and design limitations in the lenses, mirrors, and other optical materials through which the light passes prior to forming the final image of the system. Examples of such limitations might be lens aberrations, inhomogeneity and poor surface flatness of optical materials, or scintillation caused by the temporally changing optical properties of the atmosphere. For these phenomena, the effects generally increase proportionally to the area of the media traversed. Thus, a system with a larger aperture will exhibit more wave front distortion effects than a smaller aperture system with optical media of the same quality. This is why decreasing the aperture (increasing the f/stop) of an optical system may produce a sharper image.

The second phenomenon limiting resolution is the diffraction of the light caused by obstacles or edges within the optical path. (In many cases, these are the physical edges of the system's apertures.) Due to the wave nature of light, some of its energy is spread outside the area that would normally be expected for linear propagation. When light passes through an aperture of an optical system, the light energy is spread out, or "bent" around the physical edge of the aperture. This results in a point source of light at the object plane not forming a point at the image plane, but instead having some physical distribution, called the point spread function.

For a circular aperture (which is the case for most optical systems), the point spread function may be described by a first order Bessel function. The irradiance distribution is given as:

$$I_x = I_o \left[\frac{2J_1(x))}{x} \right]^2 \tag{1.1}$$

where I_o = the peak irradiance, $J_1(x)$ = the Bessel function of the first kind of order unity, and $x = \frac{\pi D}{\lambda} \sin\Theta$, λ = wavelength, D = aperture diameter, and Θ = angular radius from the pattern maximum. This distribution, called the *Airy pattern*, is shown in figure 1.2[3]. The distance to the first zero point, commonly called the radius of the Airy disk may be derived as:

$$q_1 = 1.22 \frac{R\lambda}{D} \tag{1.2}$$

where R is the distance from the aperture to the image plane. Thus for a constant distance R, the radius of the Airy disk is inversely proportional to the radius of the circular aperture.

In the context of the above discussion, resolution may be defined as the ability to distinguish two point sources at the image plane. When the two points are close together in the object plane, their distributed images may overlap. If the two points are sufficiently close, they may overlap to the extent that it is impossible to distinguish one from the other, *i.e.*, resolve them.

The combined energy density distribution (the additive sum of the squares of the point spread function) of two such points is shown in figure 1.3. There are several criteria which may be used to define the theoretical resolution limit based on this distribution (*e.g.*, Rayleigh or Sparrow Criterion). It is not important to choose a criterion here, only to

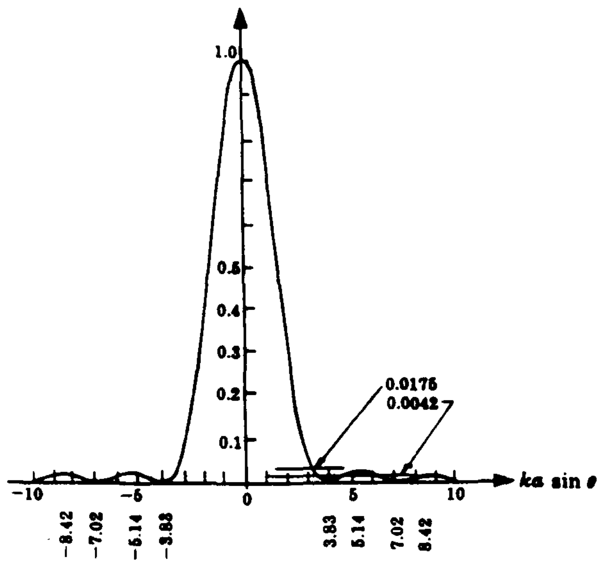

Figure 1.2: Airy distribution function.

point out that the diffraction limited resolution of an optical system ultimately depends upon the radius of the Airy disk (the half-width of the point spread function), which in turn is a function of aperture. Larger apertures produce narrower Airy disks, resulting in greater diffraction limited resolution. Small apertures yield wider Airy disks and hence poorer resolution.

The two basic phenomena influencing resolution are in opposition to one another. The effects of wave front distortion increase with aperture size, whereas diffraction effects decrease with aperture size. For a given optical system there exists an aperture size which results in optimum resolution.

1.3 Objective

The objective of the tests described in this report was to characterize the relationship between aperture and resolution for an optical system consisting of the shuttle overhead windows, the SpaDVOS zoom objective lens, and a telescope eyepiece. This included determination of the aperture size which yielded optimum resolution. The tests were conducted visually using human observers; however, a photographic test was also performed to corroborate the visual results and provide a permanent record of the test images.

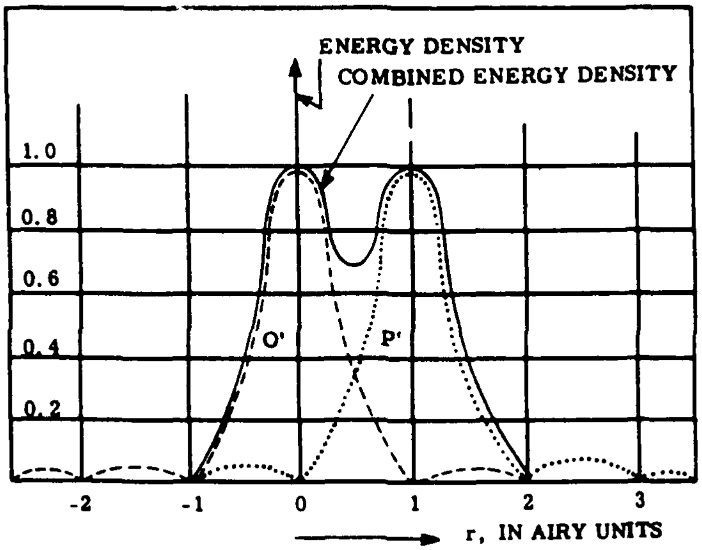

Figure 1.3: Combined Energy Distribution Function for two point sources.

1.4 Approach

An empirical approach consisting of two resolution tests was used to determine the impact of the shuttle overhead windows on the resolution observed through SpaDVOS-like optical systems. The first test was direct observation using several human observers; the second test was photographic.

In both tests the objective lens from the SpaDVOS was used to observe an Air Force 1951 tri-bar resolution target placed a moderate distance away. For the direct observation test a telescope eyepiece was attached to the lens and the observers viewed through the device at various focal lengths, aperture settings, and angles of incidence to the windows. Subjective determinations of resolution were made by statement of the group and element number of the smallest tri-bar the observer could distinguish. In the photographic test, a camera was attached to the objective lens and a series of photographs were taken at the various focal lengths, aperture settings, and angles of incidence. Limiting resolution for each condition was determined by subsequent analysis of the photographic negatives.

Method

2.1 Direct Observation Test

Test Environment and Apparatus

- *Test Environment:* The test was conducted in a laboratory at the Corning Glassworks Plant in Canton, New York. Room lights were turned off to reduce ambient light; photographic flood lights provided illumination to the resolution target. The area was relatively clean, although not a dust-free environment. The building was subject to small mechanical vibrations typical of an industrial plant, such as from moving vehicles and operating machinery.

- *Objective Lens:* Vivitar telephoto zoom, 120–600mm focal length, f/5.6, 82mm diameter.

- *Telescope Eyepiece:* Orthoscopic (Or) eyepiece, 12.5mm focal length.

- *Tripod:* Quickset model 4-52211-6.

- *Shuttle windows:* The windows used for the tests were unused spares on loan from NASA. The shuttle overhead window consists of three 20 by 20 inch transparent panes[1] mounted as shown in figure 2.1. The outer "thermal" pane is composed of 7940 fused silica and is uncoated on both sides. The middle "redundant" pane is composed of tempered 1723 alumina silicate ($ALSiO_3$), and has a high-efficiency anti-reflection (HEA) coating applied to both sides. The inner "pressure-bearing" pane is also composed of 1723 $ALSiO_3$, but has a red reflector coating applied on the cabin side and a HEA coating applied on the outer side. The windows were mounted in the same configuration as they would be installed in the orbiter using a custom mount manufactured by Corning.

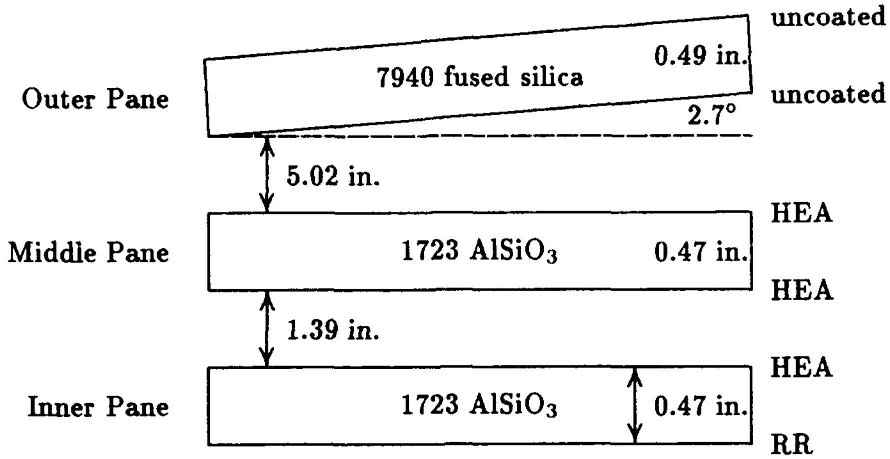

Figure 2.1: Configuration of the overhead low assembly.

Table 2.1: Table to convert group and element number into line pairs/mm for the 1951 Air Force Resolution Target.

	Groups					
Elements	-2	-1	0	1	2	3
1	0.25	0.50	1.00	2.00	4.00	8.00
2	0.28	0.56	1.12	2.24	4.49	8.98
3	0.32	0.63	1.26	2.52	5.04	10.1
4	0.35	0.71	1.42	2.83	5.66	11.3
5	0.40	0.79	1.59	3.17	6.35	12.7
6	0.45	0.89	1.78	3.56	7.13	14.3

- *Resolution Target:* Air Force 1951 tri-bar resolution target (see figure 2.2). The group and element numbers identified by the subjects during the test were converted to resolution in the units of line pairs/millimeter (lp/mm) at the target using table 2.1.

Set-up

The apparatus for the direct observation test was set up as shown in figure 2.3. Flood lights were placed on both sides of the resolution chart at 45°angles to the chart to provide a uniform illumination of approximately 520 foot-lamberts (white surface). Neoprene pads were placed under the tripod to dampen any mechanical vibrations being transmitted from the building to the optics. The Vivitar lens assembly was placed on the tripod 37 ft from

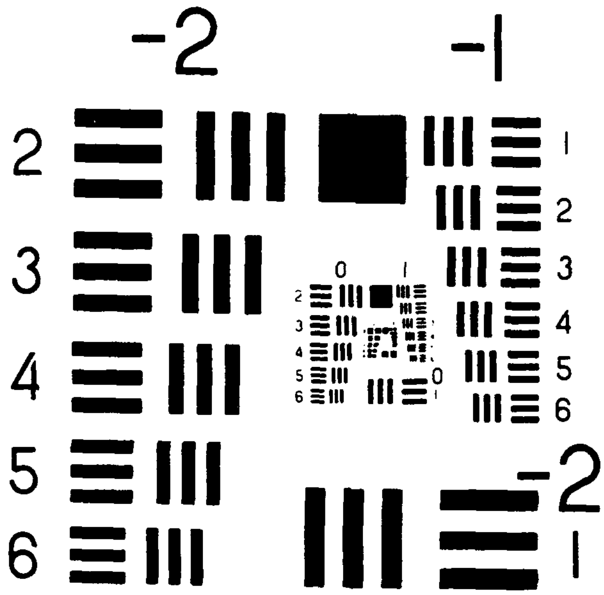

Figure 2.2: Air Force 1951 tri-bar resolution target.

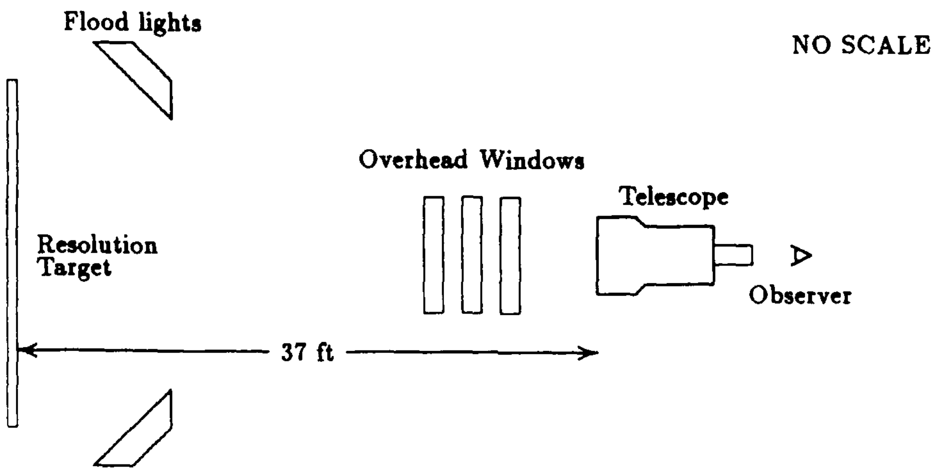

Figure 2.3: Apparatus set up for the direct observation test.

the resolution target. The Orthoscopic eyepiece was attached to the Vivitar lens using an adapter custom made by AAMRL. When present, the shuttle windows were placed approximately six inches from the Vivitar lens.

Subjects

Four observers, three male, one female, ages 24-37, with corrected visual acuity equal to or greater than 20/20 were used. (Acuity was tested using a Snellen letter chart.) All observers received identical instructions on interpretation of the resolution target. They were asked to determine the smallest set of tri-bars for which all three bars could be distinguished as straight, separate bars. If the bars appeared distorted, diffuse, or irregular, the observers were asked not to consider this as the limiting resolution set, but to use the next larger tri-bar which could be seen as three straight, distinct bars.

Procedure

1. The objective lens was directed at and focused on the resolution target (no window in place).
2. The focal length was set to 600mm and the aperture set to f/5.6.
3. Observer A adjusted the eyepiece for best focus and determined the resolution limit.
4. Step 3 was repeated at aperture settings of 8,11,16,22, and 32.
5. Steps 2 through 4 were repeated at focal lengths of 300 and 120mm.
6. Steps 2 through 5 were repeated for observers B, C, and D.
7. The window mount with the overhead windows was placed approximately six inches from the front of the Vivitar lens with the inner pane perpendicular to and centered about the line of sight from the lens to the resolution target.
8. Steps 1 through 6 were repeated.
9. The window mount was rotated 30°with respect to the line of sight to a 60°angle of incidence.
10. Steps 1 through 6 were repeated.

11. Steps 1 through 10 were repeated using each of the individual panes of the window assembly.

2.2 Photographic Test

Test Environment and Apparatus

The test environment, shuttle windows, objective lens, and resolution target were as described in section 2.1. The following additional apparatus were used for the photographic test:

Camera: Nikon F3 body with 55mm focal length macro lens and bellows adapter.

Film: Kodak technical pan 2415.

Set Up

The apparatus set up for the photographic test was similar to the direct observation set up, except the eyepiece and adapter were replaced with a macro lens, bellows, and Nikon camera (see Figure 2.4). The macro lens was placed 0.75 inches from the focal plane of the Vivitar lens, with opaque black cloth covering the area between the Vivitar and the macro lenses to eliminate stray light. A bellows was used to attach the 55mm macro lens to the Nikon F3 body. The purpose of the macro lens was to provide additional magnification so the resolution of the tri-bar image at the film plane would not be limited by the physical characteristics of the film.

Procedure

1. The lens assembly was directed at the resolution target (no window in place).
2. The macro lens was focused at infinity and its aperture set to f/8.
3. The focal length of the Vivitar was set to 600mm, the aperture set to f/5.6, and the object focus set to 37 ft.
4. The relay lens/camera system was adjusted for best focus.
5. Three exposures were taken: one at the shutter speed indicated by the camera's light meter for best exposure, and one each at a speed slower and faster.

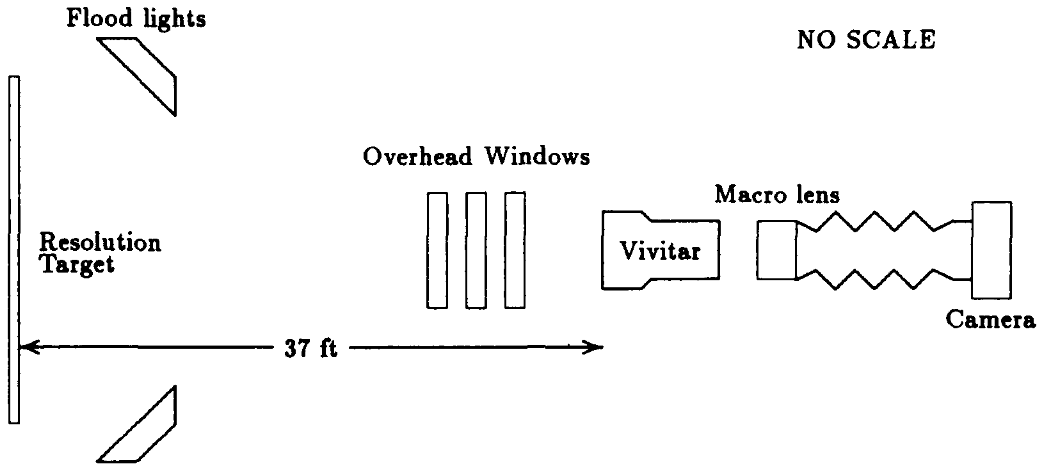

Figure 2.4: Apparatus set up for the photographic test.

6. Step 5 was repeated at apertures settings of 8, 11, 16, 22, and 32.

7. Steps 3 through 6 were repeated at focal lengths of 300 and 120mm.

8. The window mount with the overhead windows was placed approximately six inches from the front of the Vivitar lens with the inner pane perpendicular to and centered about the line of sight from the lens to the resolution target.

9. Steps 1 through 7 were repeated.

10. The window mount was rotated 30°with respect to the line of sight to a 60°angle of incidence.

11. Steps 1 through 7 were repeated.

Results

The raw data from all test conditions are included in Appendix A. The condensed results are reported in the following three sections. Section 3.1 contains the results of the direct observation test performed with the overhead window assembly, consisting of all three panes. Since this is the configuration in which the windows are used, this was the primary test of interest.

Section 3.2 contains the results of the direct observation test using the individual panes of the overhead windows. This test was of indirect interest, since the windows are never used in this configuration. However, the test was performed to see if one particular window pane was primarily responsible for distortion in the window assembly, and if so, which one.

Section 3.3 contains the results of the photographic test. This test was performed to corroborate the visual results, and is somewhat briefer than the previous two sections.

3.1 Direct Observation Test, Window Assembly

Results

The results of the direct observation test are shown in the following figures. Individual subject data were similar to the group data, so only the overall means are reported. Paired t-tests were calculated to test for differences between variables. There was no significant difference between resolution measured with horizontal or vertical tri-bars ($p = 0.21$), so all results were averaged across the two orientations.

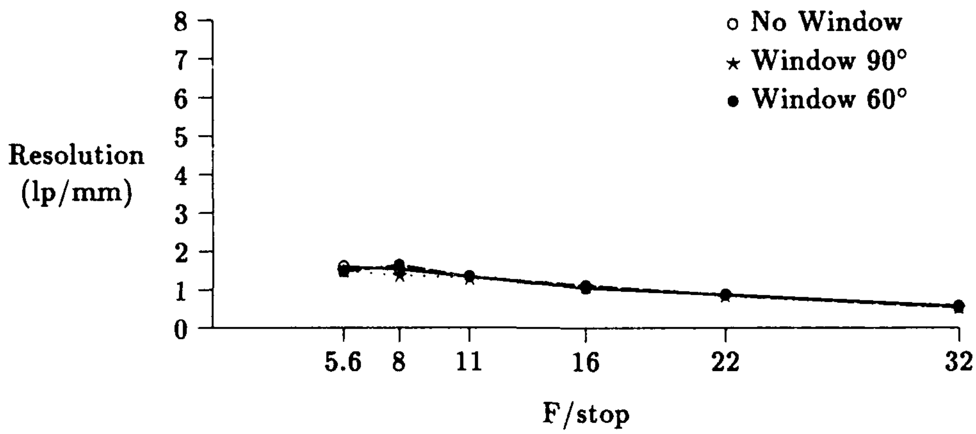

Figure 3.1: Mean resolution for 4 subjects at 120mm focal length.

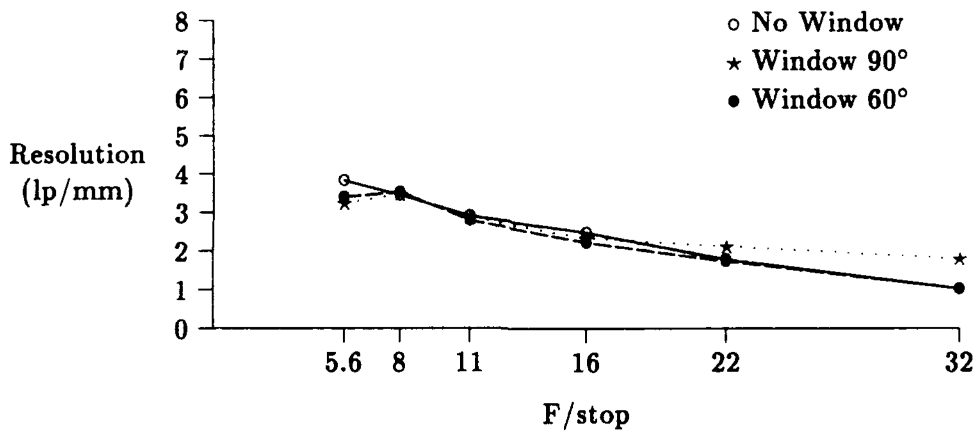

Figure 3.2: Mean resolution for 4 subjects at 300mm focal length.

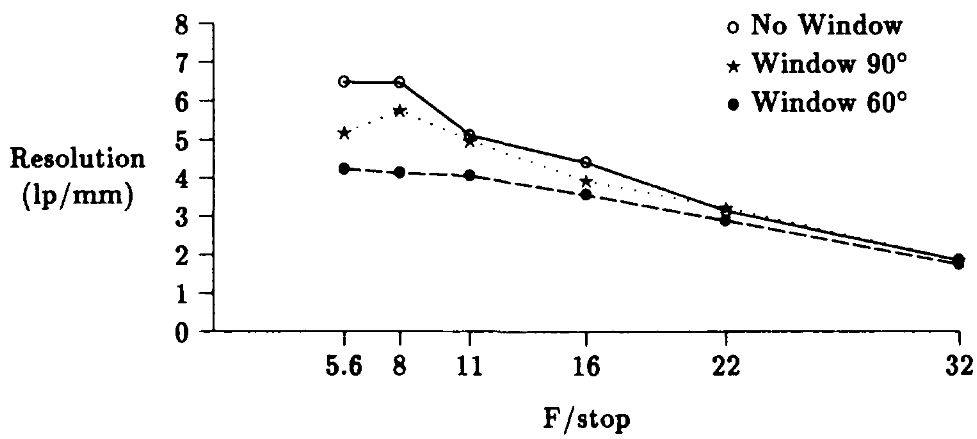

Figure 3.3: Mean resolution for 4 subjects at 600mm focal length.

The results of the paired t-tests comparing window conditions (no window (NO W), window at 90°(W 90), and window at 60°(W 60)) within f/stop and focal length are shown in tables 3.1, 3.2, and 3.3. For focal lengths of 120mm and 300mm, there was no significant change ($p > 0.05$) in resolution caused by the shuttle windows. This is apparent in figures 3.1 and 3.2 and verified by the t-test results shown in tables 3.1 and 3.2. However, figure 3.2 shows that resolution was degraded somewhat at the 300mm focal length, f/5.6 condition (largest aperture) at both the W90 and W60 conditions. For a focal length of 600mm, there were significant differences in resolution, mainly for the windows at 60°at the smaller f/stops (larger apertures). In general, window effects were significant at f/stops of 5.6, 8, and 11 but not at f/stops of 16, 22, and 32 (see figure 3.3 and table 3.3).

Table 3.1: Comparison of window condition within f/stop; FL 120mm, N=4.

f/stop	Cond Lev 1	Cond Lev 2	Mean Lev 1	Mean Lev 2	Mean Diff	Std Diff	P-value t-test
5.6	NO W	W 90	1.62	1.51	0.11	0.14	0.2095
5.6	NO W	W 60	1.62	1.49	0.13	0.16	0.1921
5.6	W 90	W 60	1.51	1.49	0.03	0.12	0.7001
8.0	NO W	W 90	1.55	1.40	0.15	0.12	0.0782
8.0	NO W	W 60	1.55	1.66	-0.11	0.17	0.2958
8.0	W 90	W 60	1.40	1.66	-0.26	0.22	0.0960
11.0	NO W	W 90	1.35	1.32	0.04	0.04	0.1817
11.0	NO W	W 60	1.35	1.35	0.01	0.14	0.9073
11.0	W 90	W 60	1.32	1.35	-0.03	0.16	0.7500
16.0	NO W	W 90	1.06	1.11	-0.05	0.06	0.2221
16.0	NO W	W 60	1.06	1.13	-0.07	0.09	0.2620
16.0	W 90	W 60	1.11	1.13	-0.02	0.09	0.7177
22.0	NO W	W 90	0.89	0.86	0.04	0.12	0.5553
22.0	NO W	W 60	0.89	0.88	0.01	0.14	0.8682
22.0	W 90	W 60	0.86	0.88	-0.03	0.05	0.3910
32.0	NO W	W 90	0.59	0.55	0.04	0.06	0.2452
32.0	NO W	W 60	0.59	0.54	0.05	0.06	0.1881
32.0	W 90	W 60	0.55	0.54	0.01	0.01	0.3910

Table 3.2: Comparison of window condition within f/stop; FL 300mm, N=4.

f/stop	Cond Lev 1	Cond Lev 2	Mean Lev 1	Mean Lev 2	Mean Diff	Std Diff	P-value *t*-test
5.6	NO W	W 90	3.84	3.25	0.59	0.53	0.1111
5.6	NO W	W 60	3.84	3.41	0.43	0.52	0.1949
5.6	W 90	W 60	3.25	3.41	-0.16	0.39	0.4734
8.0	NO W	W 90	3.46	3.49	-0.03	0.32	0.8857
8.0	NO W	W 60	3.46	3.54	-0.08	0.33	0.6634
8.0	W 90	W 60	3.49	3.54	-0.06	0.28	0.7177
11.0	NO W	W 90	2.92	2.88	0.04	0.20	0.7496
11.0	NO W	W 60	2.92	2.80	0.12	0.25	0.4029
11.0	W 90	W 60	2.88	2.80	0.08	0.17	0.3910
16.0	NO W	W 90	2.49	2.35	0.15	0.30	0.3910
16.0	NO W	W 60	2.49	2.23	0.27	0.39	0.2654
16.0	W 90	W 60	2.35	2.23	0.12	0.14	0.1817
22.0	NO W	W 90	1.79	2.14	-0.35	0.58	0.3138
22.0	NO W	W 60	1.79	1.74	0.05	0.30	0.7712
22.0	W 90	W 60	2.14	1.74	0.40	0.79	0.3910
32.0	NO W	W 90	1.03	1.81	-0.78	1.56	0.3910
32.0	NO W	W 60	1.03	1.03	0.00	0.00	*
32.0	W 90	W 60	1.81	1.03	0.78	1.56	0.3910

* Std = 0; p-value does not exist.

Table 3.3: Comparison of window condition within f/stop; FL 600mm, N=4.

f/stop	Cond Lev 1	Cond Lev 2	Mean Lev 1	Mean Lev 2	Mean Diff	Std Diff	P-value *t*-test
5.6	NO W	W 90	6.49	5.20	1.29	0.97	0.0769
5.6	NO W	W 60	6.49	4.25	2.25	0.76	0.0098
5.6	W 90	W 60	5.20	4.25	0.96	0.30	0.0076
8.0	NO W	W 90	6.47	5.76	0.71	0.57	0.0867
8.0	NO W	W 60	6.47	4.14	2.34	0.70	0.0069
8.0	W 90	W 60	5.76	4.14	1.62	0.76	0.0240
11.0	NO W	W 90	5.13	4.99	0.14	0.70	0.7223
11.0	NO W	W 60	5.13	4.07	1.05	0.52	0.0276
11.0	W 90	W 60	4.99	4.07	0.92	0.21	0.0030
16.0	NO W	W 90	4.42	3.95	0.47	0.80	0.3248
16.0	NO W	W 60	4.42	3.57	0.85	0.85	0.1389
16.0	W 90	W 60	3.95	3.57	0.38	0.09	0.0038
22.0	NO W	W 90	3.15	3.24	-0.09	0.59	0.7744
22.0	NO W	W 60	3.15	2.90	0.25	1.09	0.6779
22.0	W 90	W 60	3.24	2.90	0.34	0.56	0.3065
32.0	NO W	W 90	1.87	1.87	0.01	0.02	0.3910
32.0	NO W	W 60	1.87	1.76	0.11	0.08	0.0775
32.0	W 90	W 60	1.87	1.76	0.10	0.08	0.0820

Discussion

We found the effect of the shuttle windows on subjective resolution through a telescope was not significant at 120mm and 300mm focal lengths for the test optical system; however, resolution was affected somewhat for the 300mm focal length at the largest aperture setting (f/5.6). There was a significant effect on subjective resolution at a focal length of 600mm, particularly for the larger apertures.

It is of interest to quantify this effect and relate it to the human observer. To proceed with this analysis, the data will be transformed in two ways. First, aperture size will be substituted for f/stop, so the results may be more generally interpreted. Second, a parameter quantifying the amount of resolution degradation, called percent performance will be introduced.

Aperture size: When the Vivitar objective lens is at focal lengths of 120mm and 300mm, its aperture is simply the focal length divided by the f/stop setting indicated on the lens. However, for a focal length of 600mm at f/5.6, the aperture is not as indicated but is actually f/8.0. Table 3.4 shows the apertures realized by the Vivitar lens for the test conditions.

Table 3.4: Aperture sizes and f/stops for the Vivitar objective lens.

	aperture (inches)		
f/stop	120mm	300mm	600mm
5.6	0.84	2.11	2.95
8	0.59	1.48	2.95
11	0.43	1.07	2.15
16	0.30	0.73	1.48
22	0.21	0.54	1.07
32	0.15	0.36	0.74

Percent Performance: A parameter called percent performance (P) is defined to quantify the degree to which the shuttle windows degrade resolution.

$$P = \frac{R_w}{R_d} \times 100 \qquad (3.1)$$

where R_w is the resolution measured through the window and R_d is the resolution measured directly.

Figure 3.4 shows the percent performance at a focal length of 600mm for the windows at normal (90°) and 60°incidence. Though the data show substantial variability, there was a definite decrease in performance as aperture was increased. (Note that for the windows at 90°, f/22, performance was actually greater than 100%. This value (102%) was not significant ($p = 0.77$) and is accounted for by the variance of the data.)

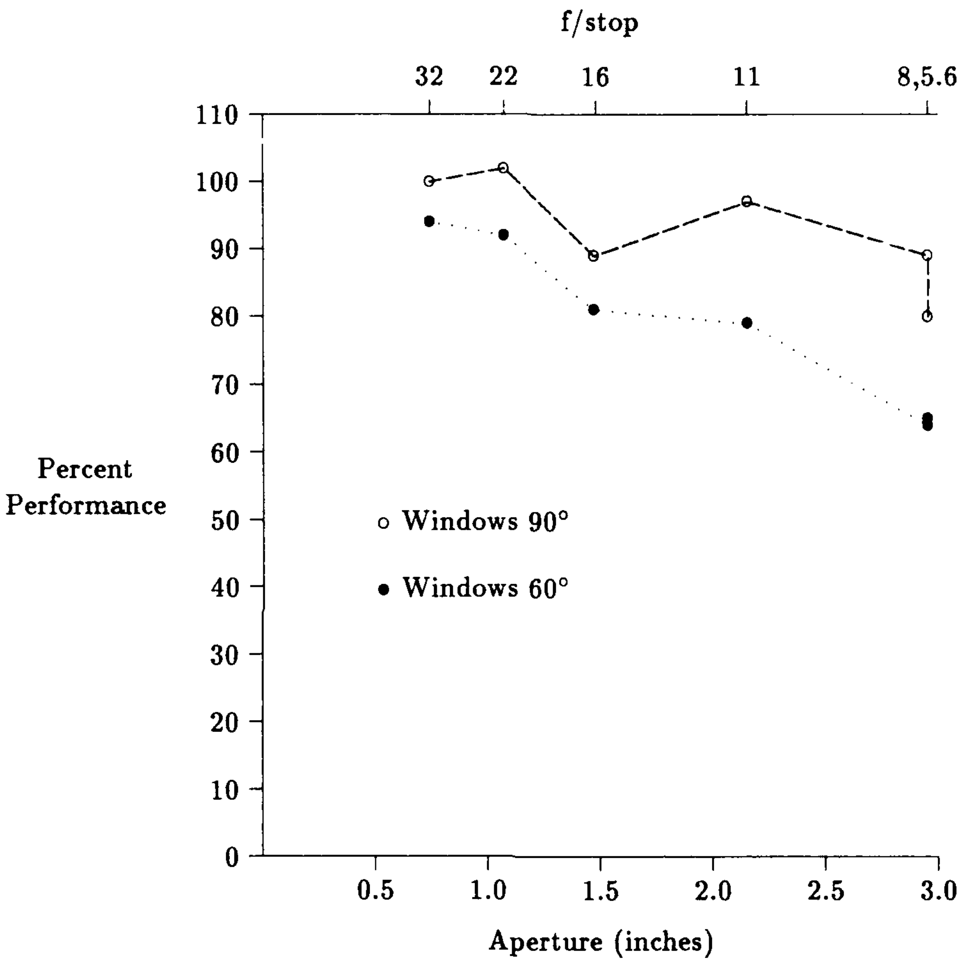

Figure 3.4: Percent performance at 600mm focal length.

Apparent Resolution: Since the eye was used as a measurement instrument for the direct observation test, it is judicious to check the data to verify the resolutions obtained were within the resolution limits of the human visual system. The nominal resolution, or acuity, of the visual system is one minute of arc, which equals 30 cycles per degree (cpd) of visual angle. This value may vary depending upon the type and conditions of the visual test employed. For example, acuities of 50 to 60 cpd are common for visual tests using gratings extending over a large portion of the visual field. [4] However, 30 cpd is a good nominal value for visual acuity.

To compare the results of the window test to the limits of the visual system, the resolution of the tri-bar target must be expressed in units of cycles per degree apparent to the subject. For this test, one millimeter at the resolution target subtended a visual angle of $\arctan(\frac{1mm}{37ft}) = 0.0051°$ at the telescope 37 ft away. Since one line pair is one cycle of the resolution pattern, 1 lp/mm = 1 cy/mm = 1 cy/0.0051°, or 196 cpd. Thus, the resolution at the target in units of lp/mm may be converted to cpd by multiplying by 196.

The subject viewed the target pattern through the telescope created by the objective lens and the eyepiece. The magnifying power (MP) of this telescope was simply the focal length of the objective lens (FL_o) divided by the focal length of the eyepiece (FL_e).

$$MP = \frac{FL_o}{FL_e} \tag{3.2}$$

For an eyepiece focal length of 12.5mm and objective focal length settings of 120mm, 300mm, and 600mm, the magnifications of the telescope were 9.6, 24, and 48, respectively. The resolution of the target pattern apparent to the subject was the resolution at the target pattern divided by the magnifying power of the telescope. Thus 1.0 lp/mm at the target viewed through a telescope with a magnifying power of 9.6 appeared as $\frac{1}{9.6}$ lp/mm, or $\frac{1}{9.6} \times 196 = 20.4$ cpd. In general:

$$\text{lp/mm at target} \times \frac{196\text{cpd/lp}}{MP} = \text{cpd apparent to observer} \tag{3.3}$$

The conditions which yielded the best resolution (no window) at each of the three focal length settings for the group subject data are shown in table 3.5. These data, which range from 26.5 to 33.0 cpd, agree reasonably well with the accepted resolution limit of the visual system. This indicates the maximum resolution measured during the no window condition was at or near the visual acuity limit.

When the windows were in place, the resolution ranged from 33.8 (120mm, f/8, W 60) to 7.2 cpd (600mm, f/32, W 60), values within the limits of the visual system. As expected, these values ranged from near the acuity limit for the higher resolutions to well below the capability of the human visual system for the lower resolutions.

Table 3.5: Best resolution results with no window.

FL (mm)	f/stop	Resolution at target (lp/mm)	Resolution apparent to subject (cpd)
120	5.6	1.62	33.0
300	5.6	3.84	31.4
600	5.6	6.49	26.5

3.2 Direct Observation Test, Individual Panes

Results

The results of the direct observation test for the individual panes of the window assembly are shown in tables 3.6 and 3.7. Table 3.6 contains the mean resolution for no window and for the window assembly (W), inner (I), middle (M), and outer (O) panes at normal incidence (90) and 60 degrees incidence (60). Table 3.7 shows the P-values from the paired *t*-test performed between the no window condition and each of the other eight conditions. P-values < 0.10 are marked with a †, and P-values < 0.05 are marked with a ‡.

Discussion

There were few cases of statistically significant differences among the data for the individual window panes, largely due to the low number of subjects. However, it is instructive to look for trends in the data by analyzing the occurrence of low P-values. For the window assembly, there were four cases of $p < 0.10$ and three cases of $p < 0.05$. For the inner pane, there are eight cases of $p < 0.10$ and two cases of $p < 0.05$. For the middle pane, two cases of $p < 0.05$ existed. For the outer pane, there were two cases of $p < 0.10$ and three cases of $p < 0.05$.

Table 3.6: Mean Resolution (lp/mm at target) for each condition (N=4).

F.L.	f/stop	NO W	W 90	W 60	I 90	I 60	M 90	M 60	O 90	O 60
120	5.6	1.62	1.51	1.49	1.42	1.47	1.42	1.47	1.47	1.53
120	8.0	1.55	1.40	1.66	1.51	1.47	1.42	1.50	1.47	1.65
120	11.0	1.35	1.32	1.35	1.36	1.38	1.29	1.29	1.35	1.45
120	16.0	1.06	1.11	1.13	1.08	1.08	1.10	1.13	1.09	1.14
120	22.0	0.89	0.86	0.88	0.86	0.83	0.84	0.84	0.88	1.28
120	32.0	0.59	0.55	0.54	0.55	0.53	0.53	0.56	0.67	0.53
300	5.6	3.84	3.25	3.41	3.34	3.48	3.44	3.30	3.39	3.36
300	8.0	3.46	3.49	3.54	3.43	3.43	3.39	3.33	3.39	3.30
300	11.0	2.92	2.88	2.80	2.76	2.84	2.78	2.84	2.80	2.90
300	16.0	2.49	2.35	2.23	2.19	2.19	2.21	2.31	2.22	2.28
300	22.0	1.79	2.14	1.74	1.69	1.67	1.73	1.69	1.77	1.74
300	32.0	1.03	1.81	1.03	1.00	1.03	1.02	1.00	1.00	1.07
600	5.6	6.49	5.20	4.25	5.61	5.64	6.20	5.99	4.80	5.08
600	8.0	6.47	5.76	4.14	5.78	5.81	6.32	6.09	4.74	5.54
600	11.0	5.13	4.99	4.07	4.91	5.06	5.06	5.42	4.44	4.84
600	16.0	4.42	3.95	3.57	3.89	4.01	3.78	4.02	3.73	3.89
600	22.0	3.15	3.24	2.90	2.92	3.06	2.89	3.38	2.90	3.15
600	32.0	1.87	1.87	1.76	1.81	1.97	1.93	1.93	1.85	1.87

Table 3.7: Comparison of Cond=NO W with the other 8 Conditions; P-values from Paired *t*-test (N=4).

F.L.	f/stop	W 90	W 60	I 90	I 60	M 90	M 60	O 90	O 60
120	5.6	0.2095	0.1921	0.0067‡	0.1483	0.3934	0.5666	0.0677†	0.4166
120	8	0.0782†	0.2958	0.3910	0.1843	0.7069	0.9017	0.1817	0.3908
120	11	0.1817	0.9073	0.9185	0.7304	0.7259	0.6621	0.9073	0.4864
120	16	0.2221	0.2620	0.3910	0.3910	0.4226	0.4226	0.1817	0.2898
120	22	0.5553	0.8682	0.5553	0.2743	0.4226	0.4226	0.8682	0.3921
120	32	0.2452	0.1881	0.0663†	0.0917†	0.1015	0.0099‡	0.4975	0.2033
300	5.6	0.1111	0.1949	0.0252‡	0.0799†	0.0490†	0.1835	0.1931	0.1346
300	8	0.8857	0.6634	0.8120	0.8754	0.8289	0.7535	0.7303	0.5005
300	11	0.7496	0.4029	0.2674	0.6593	0.4350	0.6872	0.4029	0.9444
300	16	0.3910	0.2654	0.0514†	0.0909†	0.1413	0.4055	0.1059	0.2197
300	22	0.3138	0.7712	0.5636	0.3975	0.7913	0.6300	0.8869	0.7712
300	32	0.3910	*	0.3910	*	0.4226	0.4226	0.3910	0.3910
600	5.6	0.0769†	0.0098‡	0.0731†	0.0602†	0.8187	0.4800	0.0687†	0.2532
600	8	0.0867†	0.0069‡	0.0660†	0.1001	0.8853	0.7744	0.0292‡	0.0461‡
600	11	0.7223	0.0276‡	0.4066	0.8370	0.8698	0.7830	0.0354‡	0.2722
600	16	0.3248	0.1389	0.2568	0.4098	0.2210	0.4422	0.2335	0.2568
600	22	0.7744	0.6779	0.6060	0.8636	0.5665	0.8997	0.6337	0.9891
600	32	0.3910	0.0775†	0.3910	0.3910	0.4226	0.4226	0.7001	0.9757

* Std = 0; p-value does not exist.

The data are quite dispersed and there is no evidence to indicate one pane significantly degraded the resolution through the window assembly more than the other two. The middle pane had fewer occurrences of low p-values; however, there were only three subjects for this condition (subject T had missing data) and the lower significance is due to the fewer number of subjects and not because the middle pane was of better optical quality.

3.3 Photographic Test

Results

The results of the photographic test are shown in table 3.8 and in figures 3.5, 3.6, and 3.7 in units of lp/mm at the resolution target. Since there was only one repetition, no statistical analysis was possible, other than testing for differences between horizontal and vertical orientations of tri-bars. Since there was no difference, all results were averaged across orientation.

Table 3.8: Mean resolution (lp/mm) for each Condition.

F.L.	f/stop	NO W	W 90	W 60
120	5.6	0.45	0.45	0.45
120	8.0	0.71	0.71	0.71
120	11.0	1.00	1.00	1.00
120	16.0	1.12	1.12	1.12
120	22.0	1.26	1.26	1.26
120	32.0	1.19	1.26	1.42
300	5.6	0.89	0.89	0.89
300	8.0	1.26	1.42	1.42
300	11.0	1.78	1.78	1.78
300	16.0	2.52	1.42	2.52
300	22.0	1.89	1.34	1.89
300	32.0	2.24	2.12	2.24
600	5.6	1.42	1.42	1.42
600	8.0	2.24	2.24	2.24
600	11.0	3.17	2.83	2.83
600	16.0	4.00	3.17	3.17
600	22.0	4.49	3.37	2.85
600	32.0	3.78	3.17	2.42

Discussion

The data from the photographic test vary considerably, but generally agree with the direct observation results. Figures 3.5, 3.6, and 3.7 show resolution increasing as the aperture increases, as did the previous figures for the direct observation test. There is no apparent difference in performance at the 120mm focal length for the various window conditions.

At 300mm focal length, the no window and window 60°conditions agree well, but there is a curious drop in resolution at the smaller f/stops for the window at 90°. This is believed

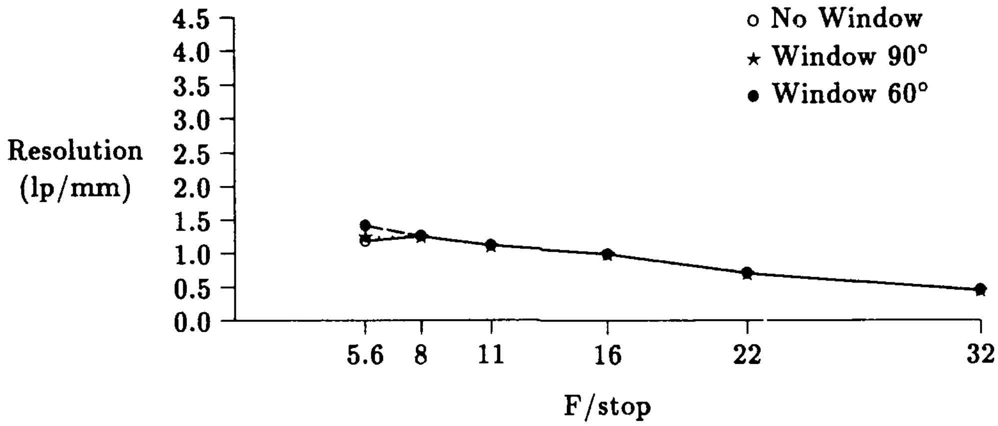

Figure 3.5: Resolution for focal length 120mm, photographic test.

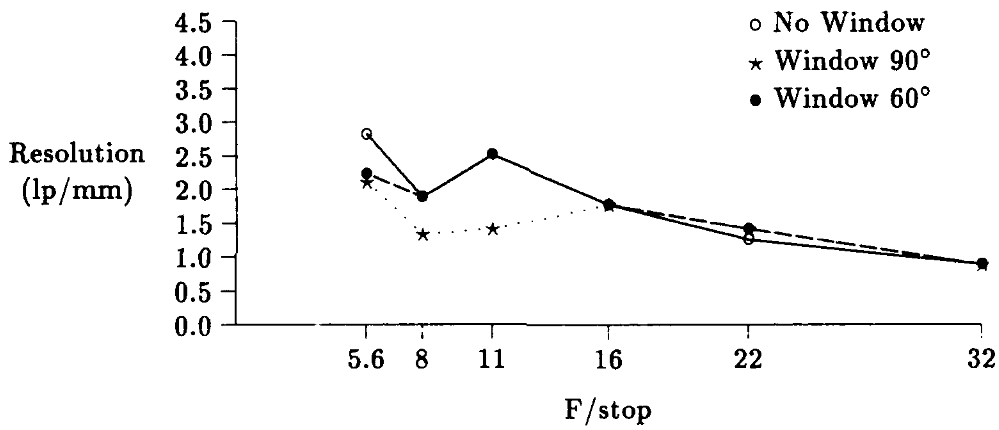

Figure 3.6: Resolution for focal length 300mm, photographic test.

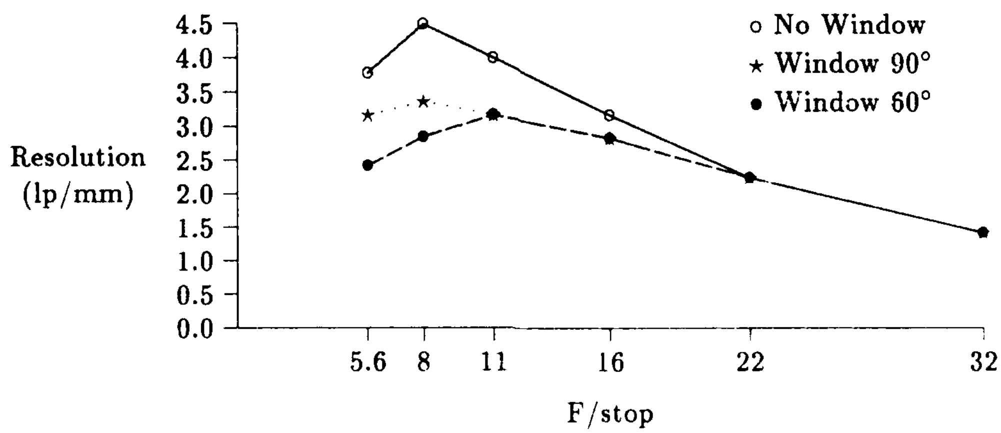

Figure 3.7: Resolution for focal length 600mm, photographic test.

to be due to a period of mechanical vibrations in the Corning plant during this part of the test. This effect was not observed during the direct observation testing.

At the 600mm focal length, the results show two important characteristics which agree with the direct observation data. First, the performance decreases for the larger apertures, and second, maximum resolution was obtained at an indicated aperture of f/8 (2.20 inches).

3.4 Aerospace Corporation Test

On the same dates the AAMRL tests were conducted, the Aerospace Corporation conducted independent tests of the overhead windows following approximately the same format but using two different objective lenses. (They also performed an interferometric test of the windows using a Zygo Mark IV interferometer.) The lenses used by Aerospace were a Celestron f/10 five inch diameter telescope and a Meade f/10 eight inch telescope. Both telescopes were of a Cassegrainian design and had no aperture adjustment.

The preliminary results of the Aerospace tests[5] indicated the percent performance (P) of the five inch diameter telescope was 66% for the visual test and 47% for photographic test. The eight inch Meade telescope had a performance of 50% for the visual test and 46% for the photographic test. These results are consistent with AAMRL test results, showing lower performance for larger aperture systems. Figure 3.8 shows the mean percent performance for the Vivitar lens at a focal length of 600mm (from the AAMRL test) with the results of the Aerospace visual tests included.

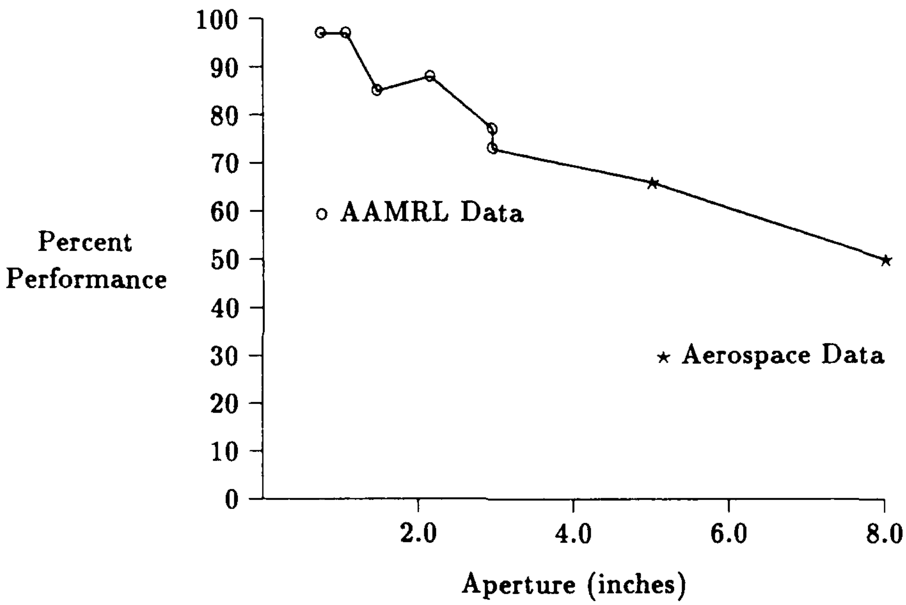

Figure 3.8: Percent performance for AAMRL and Aerospace visual tests.

Conclusions

Due to the low number of subjects and the variability in the data there were few statistically significant results from these tests. However, a number of observations were made and several trends observed.

First, resolution in general increased with aperture size at all focal lengths. This indicates the resolution obtained through the Vivitar lens was being limited by diffraction, and though wave front distortion may have been present, it was not the limiting factor except for at the largest apertures.

Second, there was a degradation in resolution at apertures greater than approximately two inches. At the shorter focal lengths (120mm and 300mm), where the aperture size ranged from 0.15 to 2.11 inches, there was no statistically significant degradation in resolution. There was, however, a visible degradation at the 2.11 inch aperture setting (f/5.6, 300mm).

Resolution was degraded for both window conditions for the 600mm focal length at apertures from 1.48 to 2.95 inches. However, this degradation was statistically significant ($p \leq 0.05$) only for the window assembly at 60°at apertures of 2.15 and 2.95 inches.

The above results imply that at an aperture of approximately two inches, the wave front distortion effects due to the window became comparable to the diffraction effects of the objective lens. As aperture was increased beyond two inches, the relative magnitude of the distortion effect increased, resulting in lower performance for the optical system. This was seen in the plot of percent performance, which showed that for the 600mm focal length, aperture was inversely proportional to performance, *i.e.*, larger apertures caused a greater performance loss than small apertures. At the shorter focal lengths, the aperture was never large enough to result in significant degradation.

Resolution degradation which was significant with the windows at 60°was not significant with the windows at normal incidence. This was probably because with the windows rotated the surface area of the windows through which the telescope viewed was larger, and thus introduced more wave front distortion.

The photographic data showed trends agreeing with the direct observation data, but by itself was inconclusive because there was only one repetition of each condition. The results of the Aerospace Corporation tests using five and eight inch aperture telescopes were consistent with AAMRL test results, and showed lower performance for larger aperture systems.

The primary purpose of this test was to determine the effect of the shuttle windows on in-cabin telescopes like the SpaDVOS. In closing, consider what the above results portend for the SpaDVOS experiment. The condition for which the subject group achieved maximum resolution through the window assembly was window 90°, FL 600mm, f/8. This resolution was 5.76 lp/mm at the target plane, which corresponds to a resolution of 1129 cpd viewed through the system with a magnifying power of 48. Assuming the optical quality of the SpaDVOS is comparable to the optical quality of the telescope used in this test, and accounting for the fact that SpaDVOS has a maximum magnification of 40, the estimated resolution through the overhead windows with SpaDVOS is 1129 cpd $\times \frac{40}{48} = 941$ cpd.

If the SpaDVOS is flown on a shuttle mission with a nominal orbital altitude of 160 nautical miles (nm), the corresponding ground resolved distance may also be calculated. One degree of visual angle viewed from the shuttle covers a distance on the Earth (at nadir) of 2.79 nm.

$$1^\circ = 2 \times tan(0.5^\circ) \times 160\text{nm} = 2.79\text{nm} \tag{4.1}$$

For a visual resolution of 941 cpd each cycle corresponds to a distance of 18 ft.

$$1\text{cycle} = \frac{2.79\text{nm/deg}}{941\text{cpd}} \times 6076\text{ft/nm} = 18\text{ft} \tag{4.2}$$

Thus, based on the results of the optical test of the shuttle overhead windows the best ground resolved distance (half a cycle) expected when viewing the earth with SpaDVOS through the overhead windows on a 160 *nm* orbit is 9 ft. Without the windows, a resolution of 8 ft would be expected (based on 6.49 lp/mm achieved for the no window, f/5.6, 600mm condition). These resolutions do not account for other factors such as vibration and atmospheric effects.

In summary, the shuttle windows may degrade resolution significantly for optical systems with apertures approximately 2.0 inches or larger. The SpaDVOS objective lens, which has a variable aperture of up to 2.95 inches, is modestly limited in resolution by the optical capabilities of the overhead window assembly; resolution would be degraded more severely for larger aperture optical systems. It is recommended that optical systems used to view through the overhead windows not use apertures greater than 2.0 to 2.5 inches in diameter until the optical quality of the windows is improved.

Appendix A: Data

This appendix contains the data from the direct observation and photographic tests. The Condition variable may be interpreted using the following key:

Table A.1: Key for test conditions.

Test Condition	
1	No window
2	Window assembly, 90°
3	Window assembly, 60°
4	inner pane, 90°
5	inner pane, 60°
6	middle pane, 90°
7	middle pane, 60°
8	outer pane, 90°
9	outer pane, 60°

A.1 Direct Observation Data

Data for Subject M (lp/mm)

FL	FSTOP	OR	1	2	3	4	5	6	7	8	9
600	5.6	H	5.66	5.04	4.00	5.04	4.49	5.04	5.04	4.49	4.49
600	8	H	5.66	5.66	4.00	5.04	4.49	5.04	5.04	4.00	4.49
600	11	H	5.04	4.49	4.00	4.49	4.49	4.49	4.49	4.49	4.49
600	16	H	4.00	3.56	3.17	3.56	3.56	3.56	3.56	3.56	3.56
600	22	H	2.83	2.83	2.83	2.83	2.83	2.83	2.83	2.52	2.83
600	32	H	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78
600	5.6	V	5.66	5.04	4.00	5.04	4.49	5.04	5.04	4.49	5.04
600	8	V	5.66	5.66	3.56	5.04	4.49	5.04	5.04	4.49	5.04
600	11	V	5.04	4.49	3.56	4.49	4.49	4.49	4.49	4.49	4.49
600	16	V	3.56	3.56	3.17	3.56	3.56	3.56	3.56	3.56	3.56
600	22	V	2.83	2.83	2.83	2.83	2.83	2.83	2.83	2.52	2.83
600	32	V	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.78	1.59
300	5.6	H	3.56	2.83	2.52	2.83	3.17	3.17	2.83	2.83	2.52
300	8	H	3.17	2.83	2.83	2.83	2.83	2.83	2.83	2.83	2.52
300	11	H	2.83	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52
300	16	H	2.24	2.24	2.00	2.00	2.00	2.00	2.00	2.00	2.24
300	22	H	1.78	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59
300	32	H	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
300	5.6	V	3.56	2.83	2.52	2.83	3.17	3.17	2.83	2.83	2.52
300	8	V	3.17	2.83	2.83	2.83	3.17	2.83	2.83	2.83	2.83
300	11	V	2.83	2.52	2.52	2.52	2.52	2.52	2.52	2.52	2.52
300	16	V	2.24	2.24	2.00	2.00	2.00	2.00	2.00	2.00	2.24
300	22	V	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59
300	32	V	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
120	5.6	H	1.41	1.26	1.26	1.26	1.26	1.26	1.12	1.26	1.26
120	8	H	1.41	1.26	1.26	1.26	1.26	1.26	1.12	1.26	1.26
120	11	H	1.26	1.26	1.12	1.26	1.26	1.12	1.00	1.12	1.12
120	16	H	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
120	22	H	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
120	32	H	0.56	0.56	0.50	0.50	0.50	0.50	0.50	0.50	0.50
120	5.6	V	1.41	1.26	1.26	1.26	1.26	1.26	1.12	1.26	1.26
120	8	V	1.41	1.26	1.26	1.26	1.26	1.26	1.12	1.26	1.26
120	11	V	1.26	1.26	1.12	1.26	1.26	1.12	1.12	1.12	1.12
120	16	V	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
120	22	V	0.79	0.79	0.79	0.79	0 79	0.79	0.79	0.79	0.79
120	32	V	0.56	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

Data for Subject K (lp/mm)

FL	FSTOP	OR	1	2	3	4	5	6	7	8	9
600	5.6	H	5.66	5.66	4.49	5.66	5.66	5.66	5.04	5.66	5.66
600	8	H	6.35	5.66	4.49	5.66	6.35	6.35	5.66	5.66	5.66
600	11	H	5.66	5.04	4.00	5.04	5.04	5.04	5.04	4.49	5.04
600	16	H	5.66	4.00	3.56	4.00	4.00	4.00	4.00	3.56	4.00
600	22	H	4.00	3.56	2.52	2.83	2.83	2.83	2.83	2.83	2.83
600	32	H	1.78	1.78	1.59	1.78	1.78	1.78	1.78	1.59	1.78
600	5.6	V	6.35	5.66	4.49	5.66	5.66	6.35	5.66	5.66	6.35
600	8	V	6.35	5.66	4.49	6.35	6.35	6.35	5.66	5.66	6.35
600	11	V	5.66	5.04	4.49	5.04	5.04	5.04	5.04	4.49	5.04
600	16	V	5.66	4.00	3.56	4.00	4.00	4.00	4.00	3.56	4.00
600	22	V	4.49	3.56	2.52	2.83	2.83	2.83	2.83	2.83	2.83
600	32	V	1.78	1.78	1.59	1.78	1.78	1.78	1.78	1.59	1.78
300	5.6	H	3.56	3.17	3.56	3.17	3.17	3.17	2.83	3.56	3.17
300	8	H	3.56	3.56	3.56	3.56	3.17	3.56	3.17	3.56	3.17
300	11	H	3.17	3.17	2.83	2.83	2.83	2.83	2.83	2.83	2.83
300	16	H	2.83	2.24	2.00	2.24	2.24	2.24	2.24	2.24	2.24
300	22	H	2.00	3.17	1.59	1.59	1.59	1.59	1.59	1.59	1.59
300	32	H	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
300	5.6	V	3.56	3.17	3.56	3.17	3.17	3.56	2.83	3.56	3.56
300	8	V	3.56	3.56	3.56	3.56	3.17	3.56	3.17	3.56	3.56
300	11	V	3.17	3.17	2.83	2.83	2.83	2.83	2.83	2.83	2.83
300	16	V	2.83	2.24	2.00	2.24	2.24	2.24	2.24	2.24	2.24
300	22	V	2.00	3.17	1.59	1.59	1.59	1.59	1.59	1.59	1.59
300	32	V	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
120	5.6	H	1.78	1.78	1.59	1.59	1.41	1.41	1.59	1.59	1.59
120	8	H	1.59	1.41	1.78	1.59	1.41	1.41	1.59	1.59	1.59
120	11	H	1.41	1.41	1.41	1.41	1.26	1.26	1.41	1.41	1.41
120	16	H	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
120	22	H	1.00	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.89
120	32	H	0.56	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
120	5.6	V	1.78	1.78	1.59	1.59	1.41	1.41	1.59	1.59	1.59
120	8	V	1.59	1.41	1.78	1.59	1.41	1.41	1.59	1.59	1.78
120	11	V	1.41	1.41	1.41	1.41	1.26	1.26	1.41	1.41	1.41
120	16	V	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
120	22	V	1.00	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.89
120	32	V	0.56	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

Data for Subject S (lp/mm)

FL	FSTOP	OR	1	2	3	4	5	6	7	8	9
600	5.6	H	6.35	4.49	4.00	5.04	5.66	7.13	7.13	4.00	1.12
600	8	H	6.35	5.04	4.49	5.04	5.66	7.13	7.13	4.00	5.04
600	11	H	4.49	5.66	4.49	4.49	5.04	5.66	6.35	4.00	4.49
600	16	H	4.00	4.00	4.00	4.00	4.49	3.56	4.49	4.00	4.00
600	22	H	2.83	3.17	3.56	2.83	3.56	2.83	4.49	3.56	3.17
600	32	H	1.78	2.24	2.00	1.78	2.52	2.24	2.24	2.24	2.24
600	5.6	V	8.00	5.04	4.49	5.66	5.66	8.00	8.00	4.00	4.49
600	8	V	7.13	5.66	4.49	5.66	5.66	8.00	8.00	4.00	5.04
600	11	V	5.04	5.66	4.49	5.04	5.04	5.66	7.13	4.00	4.49
600	16	V	4.49	4.49	4.00	4.00	4.49	4.00	4.49	4.00	4.00
600	22	V	2.52	3.56	3.56	3.17	3.56	3.17	4.49	3.56	3.56
600	32	V	2.52	2.00	2.00	2.00	2.52	2.24	2.24	2.24	2.24
300	5.6	H	4.00	2.83	3.56	3.56	3.56	3.56	4.00	3.17	3.56
300	8	H	3.56	3.56	4.00	3.56	3.56	3.56	4.00	3.17	3.17
300	11	H	2.83	2.83	2.83	2.83	2.83	2.83	3.17	2.83	2.83
300	16	H	2.52	2.52	2.52	2.24	2.24	2.24	2.52	2.24	2.24
300	22	H	1.59	2.00	2.00	2.00	2.00	2.00	1.78	2.00	2.00
300	32	H	1.12	4.00	1.12	1.00	1.12	1.00	1.00	1.00	1.26
300	5.6	V	4.49	3.17	3.56	3.56	3.56	4.00	4.49	3.17	3.56
300	8	V	3.56	3.56	4.00	3.56	3.56	4.00	4.00	3.17	3.17
300	11	V	2.83	2.83	2.83	3.17	2.83	3.17	3.17	2.83	2.83
300	16	V	2.52	2.52	2.52	2.52	2.00	2.52	2.83	2.24	2.24
300	22	V	1.78	2.00	2.00	2.00	1.78	2.00	2.00	2.00	2.00
300	32	V	1.12	4.49	1.12	1.00	1.12	1.12	1.00	1.00	1.26
120	5.6	H	1.41	1.41	1.59	1.26	1.41	1.59	1.59	1.26	1.59
120	8	H	1.41	1.41	1.59	1.41	1.41	1.59	1.78	1.26	1.78
120	11	H	1.26	1.26	1.26	1.26	1.41	1.41	1.41	1.26	1.78
120	16	H	1.00	1.12	1.12	1.00	1.12	1.12	1.26	1.12	1.41
120	22	H	0.89	1.00	1.00	1.00	0.89	0.89	0.89	1.00	1.00
120	32	H	0.71	0.63	0.63	0.71	0.63	0.56	0.63	1.00	0.63
120	5.6	V	1.59	1.59	1.59	1.41	1.41	1.59	1.78	1.26	1.78
120	8	V	1.41	1.41	1.59	1.41	1.41	1.59	1.78	1.26	1.78
120	11	V	1.41	1.26	1.26	1.26	1.41	1.59	1.41	1.26	1.78
120	16	V	1.12	1.26	1.12	1.12	1.12	1.26	1.26	1.12	1.26
120	22	V	1.00	1.00	1.00	1.00	0.89	1.00	1.00	1.00	1.12
120	32	V	0.79	0.63	0.63	0.71	0.63	0.63	0.71	1.26	0.56

Data for Subject T (lp/mm)

FL	FSTOP	OR	1	2	3	4	5	6	7	8	9
600	5.6	H	7.13	5.04	4.00	5.66	6.35	.	.	5.04	6.35
600	8	H	7.13	6.35	3.56	6.35	6.35	.	.	5.04	6.35
600	11	H	5.04	4.49	3.56	5.04	5.66	.	.	4.49	5.04
600	16	H	4.00	4.00	3.56	4.00	4.00	.	.	3.56	4.00
600	22	H	2.83	2.83	2.52	2.83	2.83	.	.	2.52	3.17
600	32	H	1.78	1.78	1.59	1.78	1.78	.	.	1.78	1.78
600	5.6	V	7.13	5.66	4.49	7.13	7.13	.	.	5.04	7.13
600	8	V	7.13	6.35	4.00	7.13	7.13	.	.	5.04	6.35
600	11	V	5.04	5.04	4.00	5.66	5.66	.	.	5.04	5.66
600	16	V	4.00	4.00	3.56	4.00	4.00	.	.	4.00	4.00
600	22	V	2.83	3.56	2.83	3.17	3.17	.	.	2.83	4.00
600	32	V	1.78	1.78	1.78	1.78	1.78	.	.	1.78	1.78
300	5.6	H	4.00	4.00	4.00	3.56	4.00	.	.	4.00	4.00
300	8	H	3.56	4.00	3.56	3.56	4.00	.	.	4.00	4.00
300	11	H	2.83	2.83	2.83	2.52	3.17	.	.	2.83	2.83
300	16	H	2.24	2.24	2.24	2.00	2.24	.	.	2.24	2.24
300	22	H	1.59	1.59	1.59	1.59	1.59	.	.	1.78	1.59
300	32	H	1.00	1.00	1.00	1.00	1.00	.	.	1.00	1.00
300	5.6	V	4.00	4.00	4.00	4.00	4.00	.	.	4.00	4.00
300	8	V	3.56	4.00	4.00	4.00	4.00	.	.	4.00	4.00
300	11	V	2.83	3.17	3.17	2.83	3.17	.	.	3.17	4.00
300	16	V	2.52	2.52	2.52	2.24	2.52	.	.	2.52	2.52
300	22	V	2.00	2.00	2.00	1.59	1.59	.	.	2.00	2.00
300	32	V	1.00	1.00	1.00	1.00	1.00	.	.	1.00	1.00
120	5.6	H	1.78	1.41	1.41	1.41	1.78	.	.	1.78	1.41
120	8	H	1.78	1.41	2.00	1.78	1.78	.	.	1.78	1.78
120	11	H	1.41	1.26	1.59	1.41	1.59	.	.	1.59	1.41
120	16	H	1.00	1.12	1.26	1.12	1.00	.	.	1.12	1.12
120	22	H	0.79	0.79	0.89	0.79	0.79	.	.	0.89	0.79
120	32	H	0.50	0.50	0.50	0.50	0.50	.	.	0.56	0.50
120	5.6	V	1.78	1.59	1.59	1.59	1.78	.	.	1.78	1.78
120	8	V	1.78	1.59	2.00	1.78	1.78	.	.	1.78	2.00
120	11	V	1.41	1.41	1.59	1.59	1.59	.	.	1.59	1.59
120	16	V	1.12	1.12	1.26	1.12	1.12	.	.	1.12	1.12
120	22	V	0.89	0.89	1.00	0.89	0.89	.	.	1.00	4.00
120	32	V	0.05	0.56	0.56	0.50	0.50	.	.	0.56	0.56

Note: Missing data for subject T, conditions 6 and 7.

A.2 Photographic Data (lp/mm)

FL	FSTOP	OR	1	2	3
600	32	H	1.42	1.42	1.42
600	22	H	2.24	2.24	2.24
600	16	H	3.17	2.83	2.83
600	11	H	4.00	3.17	3.17
600	8	H	4.49	3.17	3.17
600	5.6	H	4.00	3.17	2.83
600	32	V	1.42	1.42	1.42
600	22	V	2.24	2.24	2.24
600	16	V	3.17	2.83	2.83
600	11	V	4.00	3.17	3.17
600	8	V	4.49	3.56	2.52
600	5.6	V	3.56	3.17	2.00
300	32	H	0.89	0.89	0.89
300	22	H	1.26	1.42	1.42
300	16	H	1.78	1.78	1.78
300	11	H	2.52	2.42	2.52
300	8	H	1.26	0.89	1.26
300	5.6	H	2.83	2.24	2.24
300	32	V	0.89	0.89	0.89
300	22	V	1.26	1.42	1.42
300	16	V	1.78	1.78	1.78
300	11	V	2.52	2.42	2.52
300	8	V	2.52	1.78	2.52
300	5.6	V	2.83	2.00	2.24
120	32	H	0.45	0.45	0.45
120	22	H	0.71	0.71	0.71
120	16	H	1.00	1.00	1.00
120	11	H	1.12	1.26	1.12
120	8	H	1.26	1.26	1.26
120	5.6	H	1.26	1.26	1.26
120	32	V	0.45	0.45	0.45
120	22	V	0.71	0.71	0.71
120	16	V	1.00	1.00	1.00
120	11	V	1.12	1.26	1.12
120	8	V	1.26	1.26	1.26
120	5.6	V	1.12	1.26	1.42

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